Image-Guided Teleoperation for Soft Bronchoscopy Robot

Pingyu Xiang, *Zhejiang University*, HangZhou, China, xiang_py@zju.edu.cn

Jingyu Zhang, *Zhejiang University*, HangZhou, China, jingyu_zhang@zju.edu.cn

Yue Wang, *Zhejiang University*, HangZhou, China, wangyue@iipc.zju.edu.cn

Rong Xiong, *Zhejiang University*, HangZhou, China, rxiong@zju.edu.cn

Haojian Lu*, *Zhejiang University*, HangZhou, China, luhaojian@zju.edu.cn

***Abstract*—Currently, the majority of traditional bronchoscopes require skilled doctors to manually insert them through the patient's nose or mouth into the airway, where a slight mistake can lead to severe consequences like tracheal perforation or pneumothorax. In order to address this issue, This paper introduces a soft bronchoscopy robot designed to align with human intuition during operation. By employing U-Net to process the image of the airway, a method based on artificial potential fields is proposed, which introduces a force feedback mechanism to intervene in the operator's actions, thereby enhancing the safety and reliability of bronchoscopy procedures performed remotely. The presented robotic system and approach are validated for safety and reliability on a human lung bronchial model.**

***Index Terms*—bronchoscopy robot, teleoperation, soft robot**

I. Introduction

Respiratory system diseases seriously endanger human life and health, such as lung cancer [1], chronic obstructive pulmonary disease (COPD) [2], and the global pandemic of novel coronavirus pneumonia (COVID-19). For this series of diseases, early diagnosis is a crucial and necessary step for successful treatment. In addition to traditional open surgeries, minimally invasive surgeries (MIS) assisted by bronchoscope robots are widely used in clinical practice due to their advantages of small or even no incisions, faster recovery, and fewer postoperative complications. When conducting this kind of surgery, an experienced doctor would insert a soft bronchoscope carefully through the patient's mouth or nose to visualize the interior of the airways, and the reserved working channel in the robot allows for the insertion of small surgical instruments, such as biopsy forceps, enabling doctors to perform complex and precise interventions.

However, the intricate and multi-level branching structure of the bronchi continues to present a challenging task in guiding the bronchoscope to the target airway region. Currently available bronchoscopes on the market vary in quality, and while rigid bronchoscopes have largely been replaced by flexible endoscopes, issues still persist. These include excessive dependence on the operator's experience during manual insertion, inflexible and imprecise positioning, and the potential for complications. With the continuous advancement of teleoperation and communication technologies, teleoperated robots have shown tremendous potential in the medical, surgical, and rehabilitation fields [3]–[5]. They offer the ability to provide visual feedback to the medical professional, allowing for remote minimally invasive surgeries, significantly reducing surgical complexity, and risks.

Incorporating force feedback into the control loop, in addition to visual feedback, is another crucial factor [6]. Currently, commercially available endoscopy systems are rarely equipped with true force feedback mechanisms, making this a prominent area of current research. Force feedback is essential because it greatly enhances the operator's situational awareness and realism, which holds paramount importance for surgical outcomes and success rates.

Therefore, in order to further address the operational challenges, high learning curve, and lack of force feedback in the current clinically used bronchoscope robot, we propose a control framework and remote-operated bronchoscope robot system. This framework aims to integrate teleoperation, image processing, and force feedback technologies seamlessly into the control of traditional bronchoscope robots, providing a safer, more intuitive, and user-friendly approach for medical practitioners and patients. Specifically, we propose a teleoperated bronchoscope system with force feedback, achieved through image processing and deep learning techniques to construct an artificial potential field, indirectly introducing force perception into the control loop.

II. Teleoperation Bronchoscopy Robot system

The control flow of this image-guided teleoperated bronchoscope system is illustrated in Fig. 2. The operator controls a teleoperation joystick from a remote location, and the control program applies the teleoperation mapping described below to transmit motion commands from the master end to the bronchoscope robot at the slave end. The bronchoscope follows these instructions to reach the corresponding configuration and moves forward or backward as per the operator's commands. Equipped at the tip of this automated bronchoscope robot is a miniature camera that captures real-time 2D images of the human airway's interior so that the operator could observe the specific conditions inside the patient's trachea during the surgical procedure.

*Corresponding Author

This work was partly supported by the Zhejiang Provincial Natural Science Foundation of China (LD22E050007), Fundamental Research Funds for the Zhejiang Provincial Universities (2021XZZX021), Science and Technology on Space Intelligent Control Laboratory (2021-JCJQ-LB-010-13).

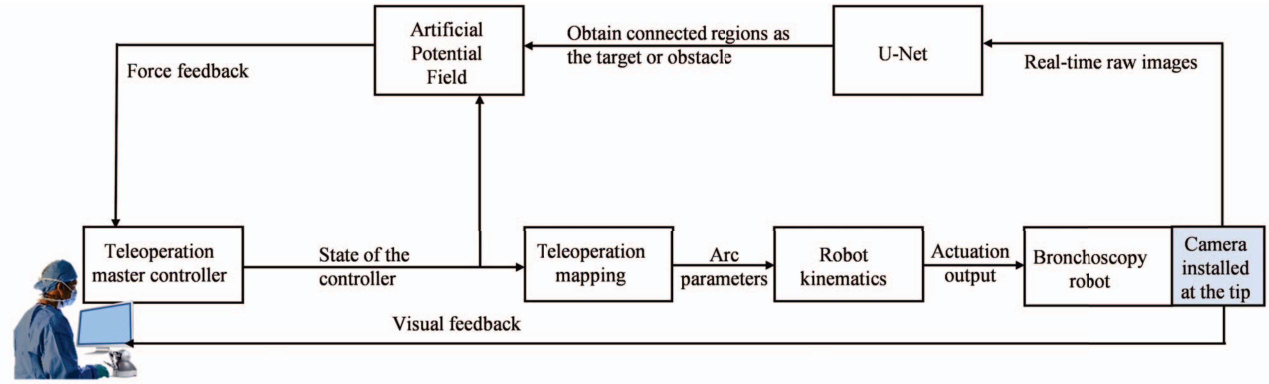

Fig. 1. Block diagram of image-guided teleoperation of Tracheal intubation.

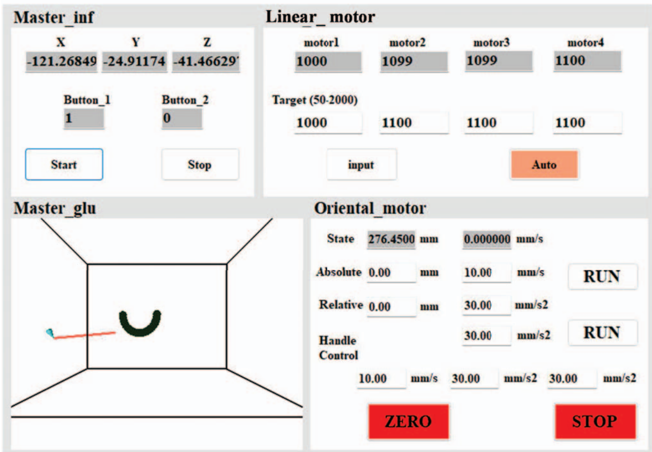

Fig. 2. Software UI of the teleoperated bronchoscopy robot system.

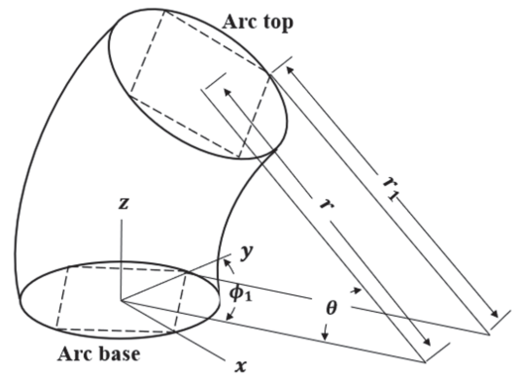

Fig. 3. Structure diagram and geometric relationship of the tendon driven continuum robot.

Once the image information is obtained, it is input into a U-Net neural network that has been trained on small samples to produce pixel-level classification results. These results determine which pixels represent the airway walls and which pixels correspond to further navigable airways. The binary image is then appropriately filtered, and connected regions are extracted. Based on this information, a virtual artificial potential field is constructed, where the robot experiences attractive and repulsive forces synthesized into a resultant force. This resultant force is projected onto the operator's teleoperation master hand at the remote end to guide the operator's actions, ensuring the overall safety and reliability of the procedure and reducing the risks associated with possible errors.

Fig. 3 displays the control software user interface (UI) of this teleoperated robotic system. The top left corner shows "Master_Inf," which reads real-time joystick positions and button information. The top right corner contains the "Linea_motor", responsible for controlling four linear motors connected to the robot's end through steel cables, enabling the robot to bend in different directions based on different commands. The bottom left corner is "Master_gle", presenting the current visualization of the robot's configuration deduced from the teleoperation mapping, represented by a fixed-length arc. The bottom right corner is "Oriental_motor", displaying the interface for controlling specific parameters of the electric sliding platform, such as speed and acceleration.

III. Method

A. Kinematics and Teleoperation Mapping of Bronchoscopy Robot

The distal end of the bronchoscope robot can be considered as a continuum robot, which theoretically possesses an infinite number of degrees of freedom and exhibits a flexible elongated body. It is precisely due to these characteristics that it plays a vital role in minimally invasive medical surgeries (MIS). Currently, a widely used modeling method for continuum robots is to approximate their configurations as a standard arc. By controlling the motion of the driver, the arc can be bent with varying curvatures and directions, as shown in Fig. 4.

According to the Piecewise constant curvature (PCC) assumption [7], the forward kinematics of the continuum robot with 4 tendons are expressed as follows,

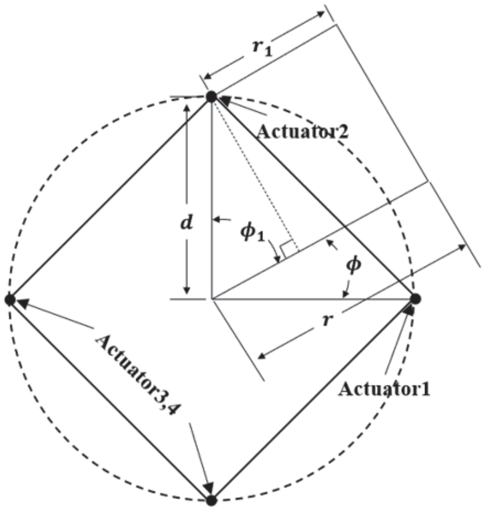

Fig. 4. cross-section view of the continuum robot.

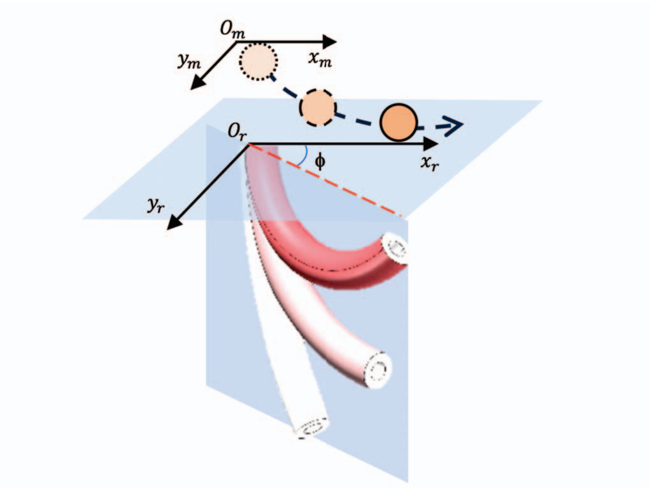

Fig. 5. Relationship between the joystick position and continuum robot's configuration.

$$l = l_i + \theta d \cos(90i - \phi) \tag{1}$$

$$\sin(\phi) = \sin(\tan^{-1}(\frac{l_4 - l_2}{l_3 - l_1})) \tag{2}$$

$$k = \frac{(l_2 + l_3 + l_4 - 3l_1)\sqrt{(l_4 - l_2)^2 + (l_3 - l_1)^2}}{d(l_1 + l_2 + l_3 + l_4)(l_4 - l_2)} \tag{3}$$

where l_i represents the length of the ith tendon pulled by the ith actuator as in Fig. 5, and The sum of these four tendon lengths is four times the length of the robot's central axis l. d represents the distance between the tendon and the center of the robot's cross-section. ϕ and k represent the bending plane angle and curvature of the robot, respectively. It's worth noting that we assume the robot can't be compressed, so that ϕ and k could fully define the robot's configuration.

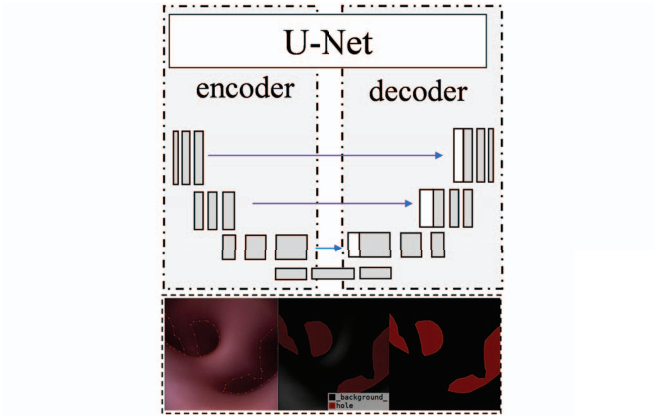

Fig. 6. The structure diagram of U-net consisting of a encoder and a decoder, and the segmentation of tracheal images.

In teleoperation control, a crucial aspect is to establish a one-to-one mapping between the motions of the master and slave ends, enabling effective and intuitive commands to be transmitted to the remote robot. In this work, the master end utilizes a game controller, while the slave end is a continuum robot. We adopt the approach from [8] to establish a direct mapping between their movements, as illustrated in Fig. 5. For instance, as the game controller moves further away from the center, the robot's bending degree increases, and the bending direction is determined by the orientation of the controller, as illustrated below.

$$k = k_{\max}\sqrt{{x_m}^2 + {y_m}^2} \tag{4}$$

$$\phi = \tan^{-1}(\frac{y_m}{x_m}) \tag{5}$$

where $k_{\max}$ is the maximum curvature the robot could tolerate. x_m and y_m represent the normilized coordinates of the master joystick.

B. U-net in Tracheal identification

The obtained images from the bronchoscope robot are processed using U-Net [9], a convolutional neural network architecture widely used for biomedical image segmentation. U-Net comprises a contracting path for feature extraction and an expansive path for precise segmentation. Its unique U-shaped structure efficiently captures contextual information and generates accurate pixel-level predictions, making it well-suited for segmenting the tracheal airway. An illustrative example of the network's architecture for tracheal airway segmentation is shown in Fig. 6.

C. Artificial Potential Fields

The artificial potential field is a classic robotic path planning algorithm that simulates a robot's motion as a charged particle experiencing forces in a magnetic field [10]. The goal location

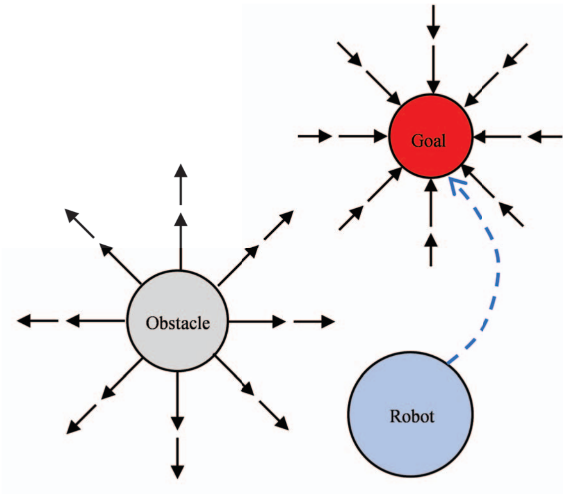

Fig. 7. Schematic diagram of the artificial force potential field, and the trajectory of a robot after being subjected to gravitational and repulsive forces in the force field.

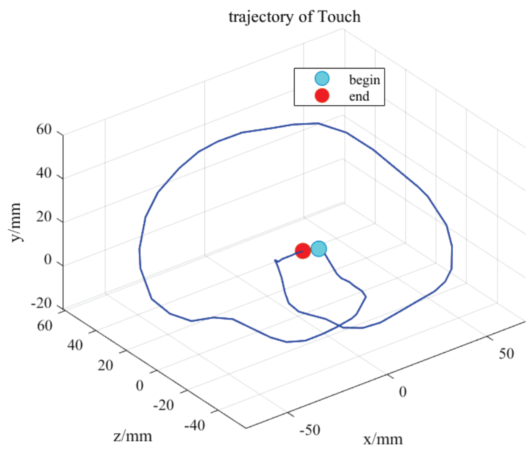

Fig. 8. The 3D trajectory of the joystick.

exerts an attractive force on the robot, while obstacles apply repulsive forces, guiding the robot's movement in complex environments as illustrates in Fig. 7.

We incorporate the concept of the artificial potential field into the force feedback of the teleoperation control for the bronchoscope robot. Based on the pixel-level tracheal airway information obtained in the previous section, we can construct an artificial potential field and calculate the magnitude and direction of the resultant force that the robot should experience in its current state. This information is then reflected on the operator's control handle to guide the robot's movement effectively.

IV. Experiment Results

We first conducted control tests between the master hand and the bronchoscope robot. The teleoperation joystick was maneuvered within its workspace to draw a circular path with a

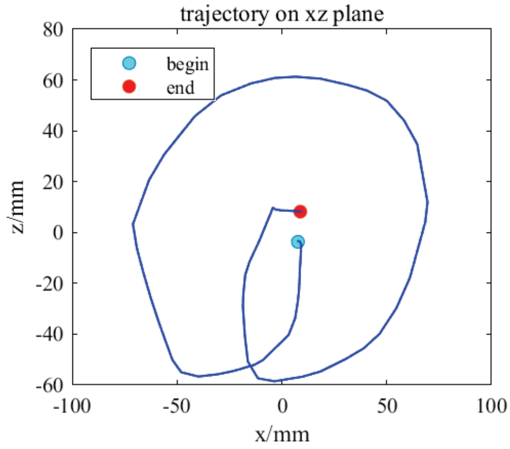

Fig. 9. The xz projection of the trajectory.

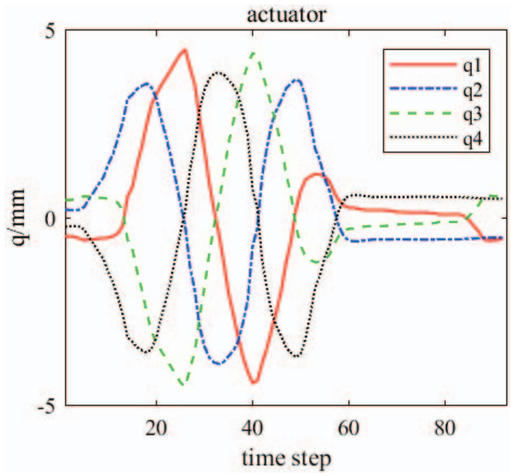

Fig. 10. The driving amount of the bronchoscope robot after the joystick moves along the trajectory of a circle.

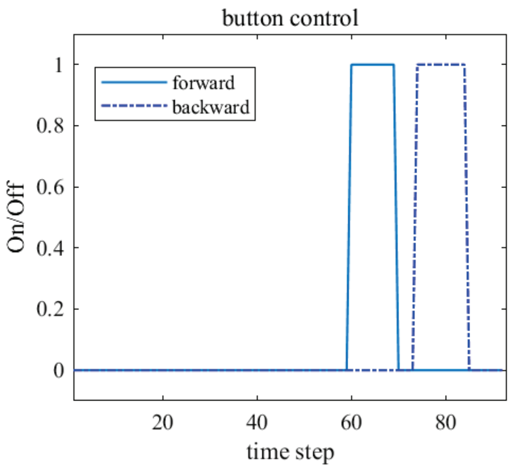

Fig. 11. The button state of the master controller.

radius of approximately 60mm in the xz plane (The coordinate system of the joystick is defined differently from the one

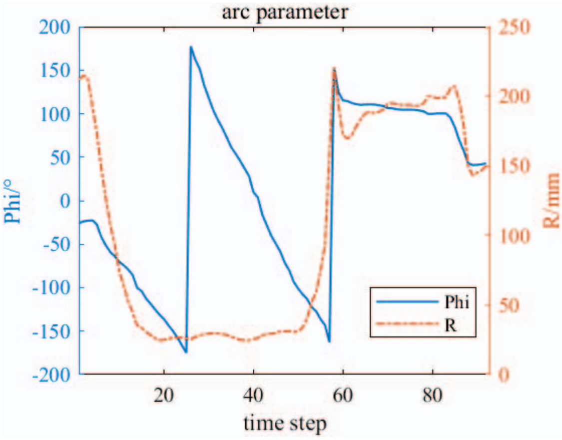

Fig. 12. The configuration parameters of the bronchoscope robot in the control test.

mentioned earlier in the text, but it does not affect the overall process), as shown in Fig. 8. The trajectory's starting and ending points are marked in blue and red, respectively. As mentioned earlier, the teleoperation mapping algorithm uses only the xz coordinates of the joystick, so the projection of the trajectory onto the xz plane is needed, as shown in Fig. 9.

Under this circular control command, the driving quantities of the four linear motors of the bronchoscope robot are illustrated in Fig. 10. According to (1), opposing actuators should have equal driving quantities with opposite directions. As the control trajectory is circular, the driving quantities exhibit a sinusoidal pattern with a nearly constant amplitude, corresponding to the robot's kinematics mentioned earlier.

For time steps greater than 60, we also tested the buttons on the control handle to control the robot's forward and backward movement, as shown in Fig. 11.

Fig. 12 demonstrates the configurations of the remote robot as the master handle draws a circular path. For time steps less than 30, the control point moves outward from the center of the circle, causing the curvature of the bronchoscope robot to gradually increase, and the represented arc's radius decreases from 200mm to 30mm. For time steps between 30 and 60, the control point orbits around the circle's center, maintaining a constant curvature while the bending plane angle linearly decreases from 180 degrees to -180 degrees.

Subsequently, we further validated our proposed robot system and algorithm in a human lung bronchial model. Through teleoperation control, the robot gradually navigated deeper into the bronchus, reaching the third level of the bronchus and successfully reaching the target point, as shown in Fig. 13.

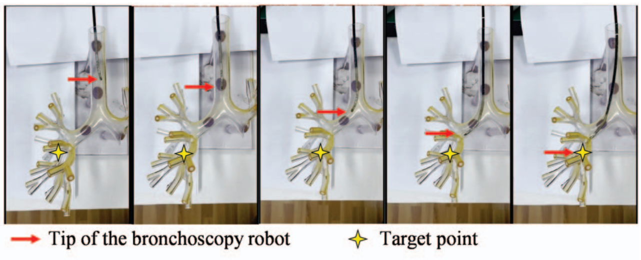

Fig. 13. Intubation experiment in a human bronchial model.

V. Conclusion and Discussion

As continuum robots play an increasingly important role in MIS, new robotic control methods have become a hot research topic, and teleoperation is one of them. To enhance the situational awareness and reliability of teleoperated surgeries, this paper proposes an image-guided teleoperation for soft bronchoscopy robot. The feasibility and reliability of the method are demonstrated through modeling, teleoperation mapping, and experimental validations. This work provides an alternative feasible solution for controlling the bronchoscope inspection surgery system with human-in-the-loop. In future research, we will further enhance the autonomy of the bronchoscopy robot and explore the potential of endowing small-scale continuum robots with more sensory capabilities, aiming to further lower the barrier of surgical operations and enhance the immersion and reliability of remote-operated surgeries.

References

[1] A. C. Arroliga and R. A. Matthay, "The role of bronchoscopy in lung cancer," *Clinics in chest medicine*, vol. 14, no. 1, pp. 87–98, 1993.

[2] C. Raherison and P. Girodet, "Epidemiology of copd," *European Respiratory Review*, vol. 18, no. 114, pp. 213–221, 2009.

[3] S. Avgousti, E. G. Christoforou, A. S. Panayides, S. Voskarides, C. Novales, L. Nouaille, C. S. Pattichis, and P. Vieyres, "Medical telerobotic systems: current status and future trends," *Biomedical engineering online*, vol. 15, no. 1, pp. 1–44, 2016.

[4] S. Mehrdad, F. Liu, M. T. Pham, A. Lelevé, and S. F. Atashzar, "Review of advanced medical telerobots," *Applied Sciences*, vol. 11, no. 1, p. 209, 2020.

[5] C. Bergeles and G.-Z. Yang, "From passive tool holders to microsurgeons: safer, smaller, smarter surgical robots," *IEEE Transactions on Biomedical Engineering*, vol. 61, no. 5, pp. 1565–1576, 2013.

[6] K. Hastrudi-Zaad and S. E. Salcudean, "On the use of local force feedback for transparent teleoperation," in *Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No. 99CH36288C)*, vol. 3. IEEE, 1999, pp. 1863–1869.

[7] R. J. Webster III and B. A. Jones, "Design and kinematic modeling of constant curvature continuum robots: A review," *The International Journal of Robotics Research*, vol. 29, no. 13, pp. 1661–1683, 2010.

[8] M. Csencsits, B. A. Jones, W. McMahan, V. Iyengar, and I. D. Walker, "User interfaces for continuum robot arms," in *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2005, pp. 3123–3130.

[9] O. Ronneberger, P. Fischer, and T. Brox, "U-net: Convolutional networks for biomedical image segmentation," in *Medical Image Computing and Computer-Assisted Intervention–MICCAI 2015: 18th International Conference, Munich, Germany, October 5-9, 2015, Proceedings, Part III 18*. Springer, 2015, pp. 234–241.

[10] O. Khatib, "Real-time obstacle avoidance for manipulators and mobile robots," *The international journal of robotics research*, vol. 5, no. 1, pp. 90–98, 1986.